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Thermonuclear Damage to Wall Materials in a Dense Plasma Focus

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Erosion	Surface Cracking

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In a damage analysis of several sample materials exposed to a thermonuclear environment, dominant failure mechanisms that may occur in the high-load components and the first walls of proposed fusion reactors were identified. The synergistic effects from a fusion plasma were experimentally simulated at The Aerospace Corporation with the Mark V dense plasma focus. For short time intervals, the dense plasma focus

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simulates the wall loading from a fusion reactor. Considerable damage, on both the macroscopic and microstructural levels, was observed in materials exposed to the harsh environment. The major damage mechanisms are identified in a variety of materials, including aluminum, stainless steel, tantalum, ceramic, and graphite. Test results indicate that surface crack initiation is the most serious failure mechanism in structural materials undergoing the thermal fatigue stresses of a fusion reactor environment. Erosion processes, the primary contribution of which is the contamination of the plasma by radiative cooling, are also discussed.

PREFACE

The authors are grateful to J. D. McClelland for many valuable discussions and assistance during the early phases of the program. Thanks are also expressed to T. J. Bertone for preparing and analyzing the samples.

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I. INTRODUCTION AND BACKGROUND

The anticipated development of a concept for achieving controlled thermonuclear fusion will make unprecedented demands on the material structures used within the reactor. Whether the concept requires the utilization of magnetically confined plasmas or inertially confined laser microexplosions, the material requirements of the first wall will dictate the severest constraints on the engineering feasibility of the reactor. At this interface, wall loading from contact with the hot gaseous plasma and the accompanying radiation will subject the materials to environmental stresses never before considered. Another crucial concern is the contamination of the plasma by the ablated wall materials, which results in degradation of the reactor output by enhanced radiative cooling and the inducement of instabilities.

Because the design criteria for such reactors are not clearly defined, the dominant failure mechanisms in first-wall reactor materials are unknown. Theoretical estimates are uncertain because of synergistic effects that result from the interaction of multiple sources of radiation and the plasma itself. An obvious solution to this dilemma is to simulate the first-wall loading with a thermonuclear plasma source. A review of such simulation devices[1-3] revealed that the dense plasma focus (DPF) may prove to be a suitable test facility. In Table 1, several relevant parameters for a proposed fusion reactor are compared with the output from an existing 140-kJ plasma focus. The reactor specifications are estimated for a high-β, 3000-MW θ-pinch.[4] It can be concluded from this table that, for short time intervals, the dense plasma focus simulates the wall loading of a pulsed fusion reactor.

The Mark V 140-kJ DPF is a pulsed plasma source with a repetition rate of 1 discharge/min. Typical operating parameters are static fill pressures of 2 to 5 Torr D_2, bank voltages of 15 kV (corresponding to 80 kJ

Table 1. Comparison of Parameters for Torroidal θ-Pinch Fusion Reactor and Aerospace 140-kJ Plasma Focus Device

	Prototype Fusion Reactor	Plasma Focus (Aerospace Mark V, 140 kJ)
Thermal power	3000 MW	3000 MW
Containment time	50 msec	50 nsec
Confining field	90 kG	1 MG
Plasma temperature	10 keV	0.5 - 2 keV
Plasma density	10^{16} cm^{-3}	10^{19} cm^{-3}
Fuel cycle	D-T	D-D
Wall loading	350 W/cm^2	2.4 MW/cm^2 [a]
Power density	3000 W/cm^3	800 kW/cm^3 [a]
Wall surface temperature	600 - 1000°C	500 - 3000°C
Neutron intensity per cycle	5×10^{13} cm^{-2}	10^{8} cm^{-2} [a]
Ion intensity per cycle	10^{13} - 10^{15} cm^{-2}	10^{15} cm^{-2} [a,b]

[a] For R = 10 cm.

[b] On-axis.

of stored energy), discharge currents of 1.6 MA, and corresponding neutron yields of 10^{10} neutrons/discharge. The plasma focus is a good source of high-energy ions and neutrals and thermal x-rays and neutrons, as well as a hot, dense, deuterium plasma.

The concept of using a thermonuclear-like device to test reactor materials was investigated for several materials with different mechanical and thermal properties. The materials, which included aluminum, stainless steel, tantalum, ceramic, and graphite, were tested by placing the samples at different positions inside the experimental device (Fig. 1). Erosion of the samples, although of concern because of the possible contamination of the plasma,[5-10] was not found to be the most serious threat to the integrity of the materials; instead, crack nucleation was the dominant damage mechanism in the samples exposed to the severe thermal fatigue stresses that divertors, limiters, beam dumps, and other high-load components in fusion reactors must withstand.

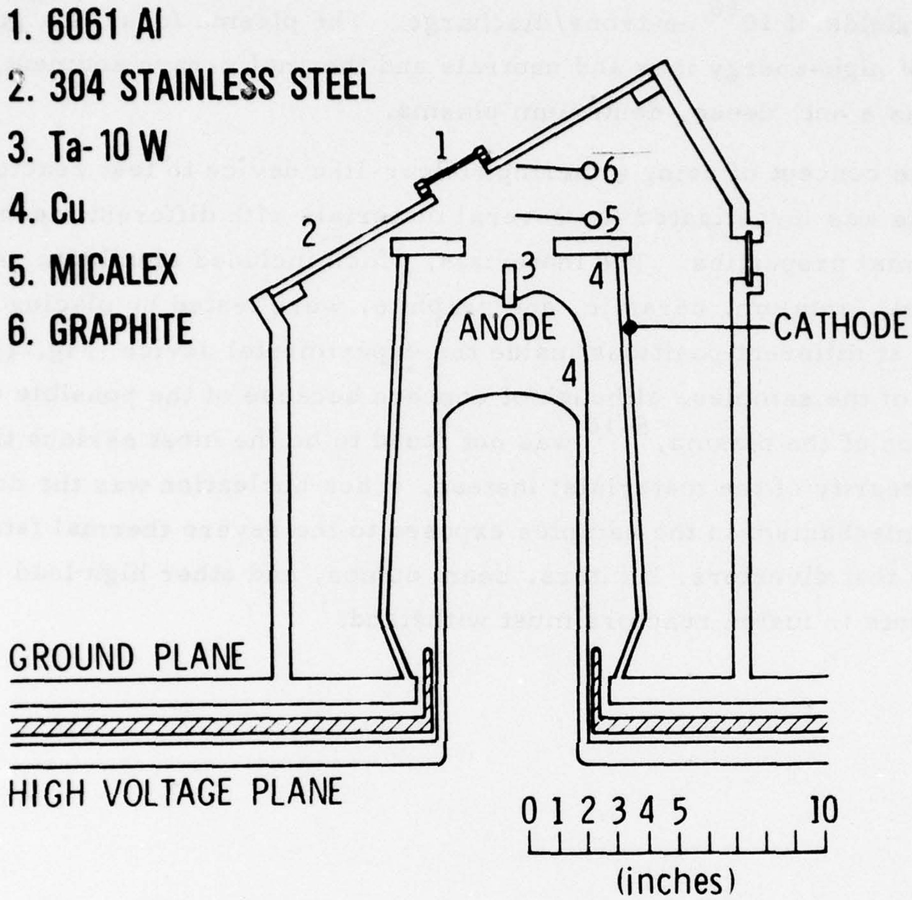

Fig. 1. Mark V Dense Plasma Focus and Designation of Test-Sample Locations

II. SURFACE DAMAGE MECHANISMS

An examination of samples exposed in the Mark V DPF simulator indicated that each material was affected, to some extent, by one or more damage mechanisms. Two major categories or causes of damage that may occur in a thermonuclear-like environment, erosion and surface crack nucleation, are shown in Fig. 2.

Erosion,[11-12] which was observed to some degree in all of the test samples, included sputtering, evaporation, and blistering. Of greatest concern in fusion reactors are chemical and physical sputtering,[13-16] pulse evaporation, and radiation blistering[17-22] resulting from the injection of hydrogen and helium atoms and ions into the wall material. These effects, which ultimately cause the material to be ablated from the wall surface, can introduce impurities into the system, resulting in contamination of the plasma. This contamination can cause radiative cooling and the inducement of plasma instabilities.

Surface crack initiation was found to be a significant cause of damage in the test samples. Molten metal deposition, thermal shock, and phase transformation were found to be possible causes of surface crack formation in materials exposed to the plasma environment. Shrinkage cracks form when a molten metal deposit, which has splattered onto the metal surface, cools and thus solidifies and contracts, causing cracks to form and propagate into the substrate metal surface. Surface cracks resulting from thermal shock are commonly observed in ceramics, wherein the steep thermal gradients that occur in brittle and nonheat-conductive materials result in large stress gradients. Strain-induced martensitic transformation in the austenitic stainless steels can increase the magnetic permeability and cause volumetric changes, which produce surface stresses that result in crack initiation. Also, the freshly transformed martensite will become susceptible to hydrogen stress cracking.

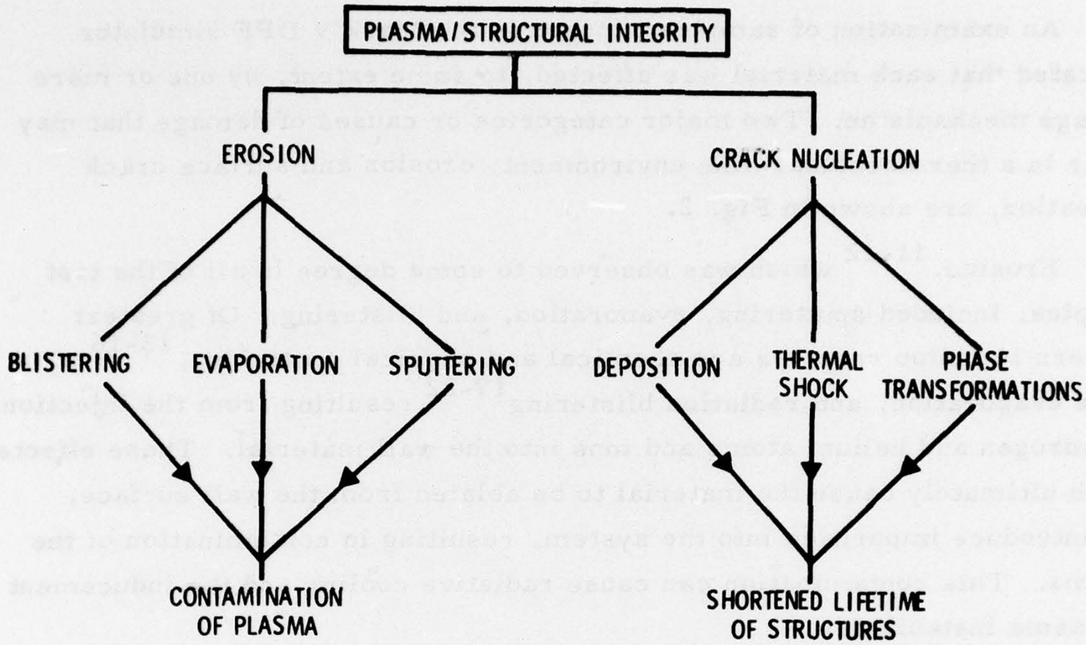

Fig. 2. Surface Damage Effects in First-Wall Materials for Fusion Reactors

Characterization of these and other cracking processes is necessary for the determination of the structural integrity of a material in a thermal fatigue environment. In a fusion reactor, for example, the number of thermal loading cycles possible before crack formation begins may represent a large percentage of the total lifetime of the structure.

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III. EXPERIMENTAL CONDITIONS

Test conditions differed for each sample (Table 2). The number of exposures, distance from the plasma pinch, and initial surface conditions for each material are given. Samples were exposed to one or more discharges from the DPF, after which a damage analysis was performed.

Table 2. Test Conditions for Samples Exposed to DPF

Sample Material	Initial Surface Condition	No. of Exposures	Minimum Distance from Plasma Pinch, cm
6061 aluminum	T6 bar stock	100	10
304 stainless steel	Annealed plate	4000	10
90 tantalum-10 tungsten	Rolled rod	500	0
Micalex[a]	Machined surface	20	4
Polycrystalline graphite	Polished surface	1	10

[a] Ceramic consisting of mica (layered Al_2O_3-SiO_2) flakes in a silicate binder.

IV. EXPERIMENTAL RESULTS

All of the metal samples were seriously damaged by cracking caused by molten metal transfer and were eroded by evaporation. In addition, the stainless-steel sample sustained phase transformations that changed the magnetic properties of the surface, and may have caused some cracking. The nonmetallic samples, i.e., the ceramic and graphite, exhibited totally different damage processes. The ceramic was primarily affected by thermal shock. However, sputtering and evaporation were the major causes of damage in the graphite, which ultimately could result in contamination of the plasma by the expelled carbon atoms.

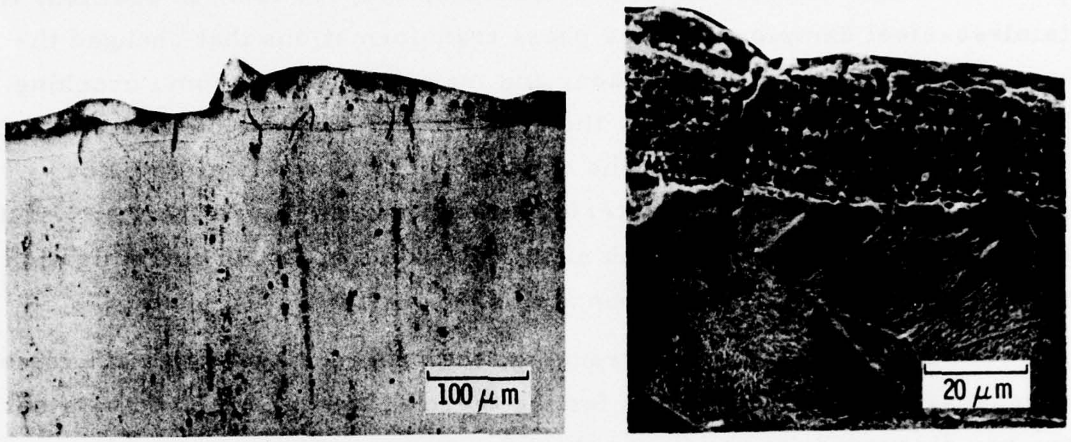
The origin and extent of cracking, the presence and effect of erosion processes, and some estimates for the thermal loading received by a surface are discussed for the five materials studied. These materials represent a wide range of mechanical and thermal properties embracing the full spectrum from ductile-to-brittle materials with low-to-high melting points.

A. ALUMINUM

Examination of the surface and the transverse aluminum section (Fig. 3) indicated that metal removal by molten-metal transfer and evaporation were the major damage mechanisms. Intergranular cracks were observed in the core material up to depths of 20 μm.

B. STAINLESS STEEL

Most of the surface of the nonmagnetic, austenitic, 304-grade stainless steel plate is covered by a deposit of molten stainless steel that has magnetic properties (Fig. 3). A magnetic particle inspection indicated that the areas with the highest magnetic intensity coincided with the areas with the largest degree of molten metal accumulation. Cracking, initiated in the molten surface layers, penetrated 20 to 25 μm into the base steel plate.



(a) (b)

Fig. 3. Surface Crack Initiation in (a) Aluminum and (b) Stainless Steel Caused by Molten Metal Deposition

Near the center of the plate (Fig. 4), the portion of the surface that was ablated by high-energy incident deuterium ions and neutrals is non-magnetic. A considerable amount of the base metal eroded or transferred away from this area. Traces of nickel impurities, a constituent of 304 stainless steel, were found in other parts of the experimental chamber by means of the ion microprobe mass analyzer (IMMA), indicating that some evaporation also occurred.

Localized melt zones were found between the molten metal deposit and the base material. No apparent grain growth, as a result of heating, occurred in these areas; thus, it can be inferred that these zones were not subjected to temperatures greater than 815°C in reheatings after the initial melting. Shrinkage cracks occurred in the columnar grain of the localized melting areas.

C. TANTALUM

The top surface of the tantalum pin was in contact with the plasma pinch and subsequent shock waves. Evidence of melting indicated that the surface attained a temperature greater than 3050°C. No molten metal deposits or surface cracks were observed on the top surface, which was physically deformed by the effects of temperature and pressure.

The side of the tantalum pin had a molten metal deposit 20 to 30 μm deep, which corresponds to the electrical skin depth of 28 μm calculated from the known discharge current of the DPF. Shrinkage cracks penetrating 10 to 20 μm into the base material were evident. An increase in hardness (from 85 Rockwell B to 42 Rockwell C) from the base material to the molten surface layers was attributed to the presence of nickel and copper impurities in the molten deposit. The surface cracking in the tantalum and the difference in size of the hardness penetrators are shown in Fig. 5.

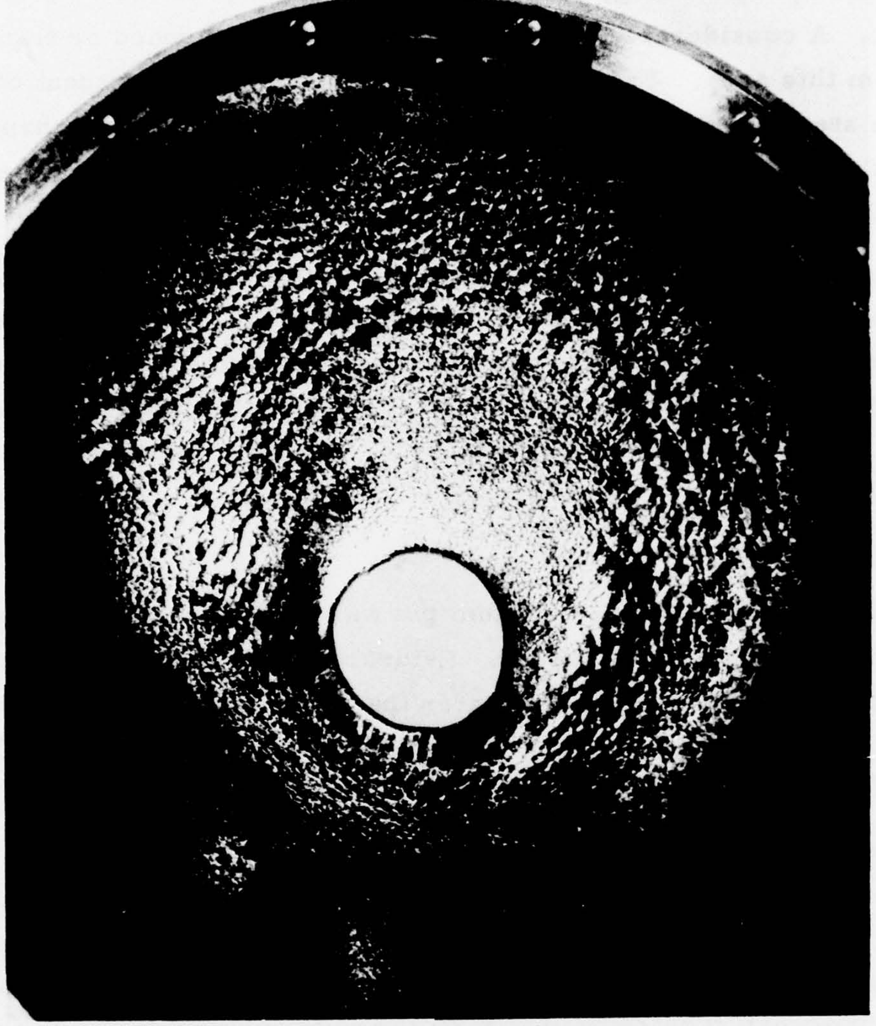


Fig. 4. Ablated Region Above Center Hole Surrounded by Areas of Molten Metal Deposition on Stainless-Steel Plate After 4000 Discharges

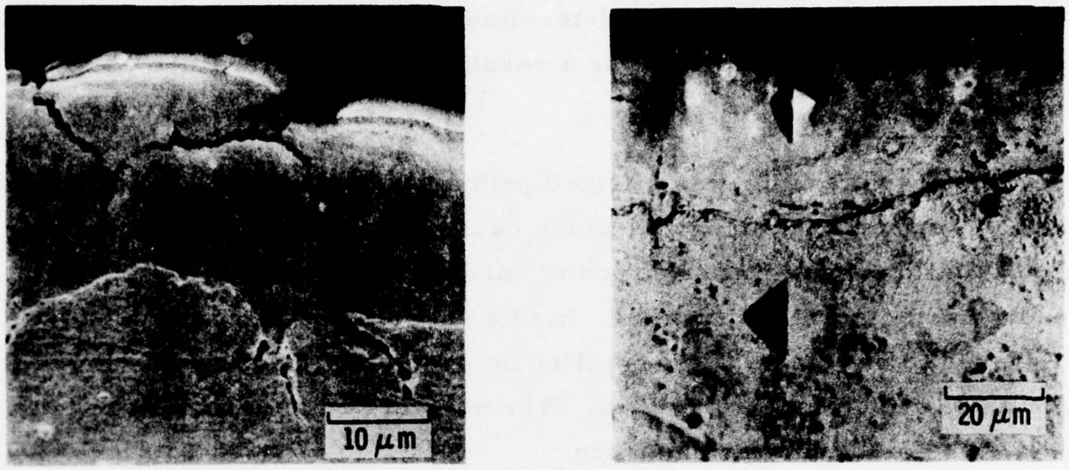


Fig. 5. Surface Cracking and Increased Hardness in Molten Metal Surface Layers in Tantalum Rod After 500 Discharges

D. CERAMIC (MICALEX)

Thermal shock was the cause of much of the damage in the Micalex sample. Surface cracking to the ceramic plate from this damage mechanism is shown in Fig. 6. It was also determined that the glassy phase of the ceramic had melted and crazed as a result of high-temperature pulsing.

E. GRAPHITE

The graphite liner was affected primarily by erosion, which was the result of surface sputtering and which caused grain-boundary cavitation. This cavitation, resulting from ion etching by an incident deuteron beam, produced some surface cracking. In this case, the surface cracking was considered to be minor, although it could eventually cause spallation of the graphite particles into the plasma. The surface of the graphite is shown in Fig. 7 before and after exposure.

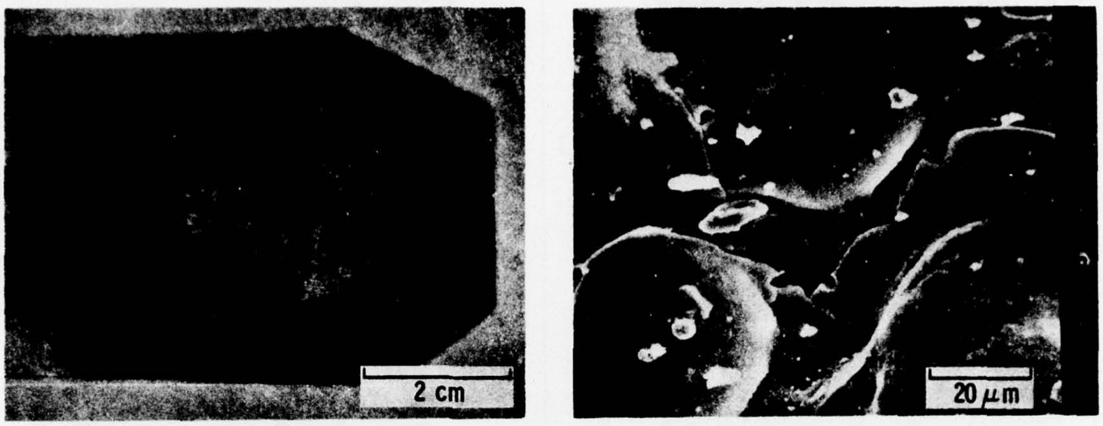


Fig. 6. Surface Cracking in Ceramic as Result of Thermal Shock After 20 Discharges

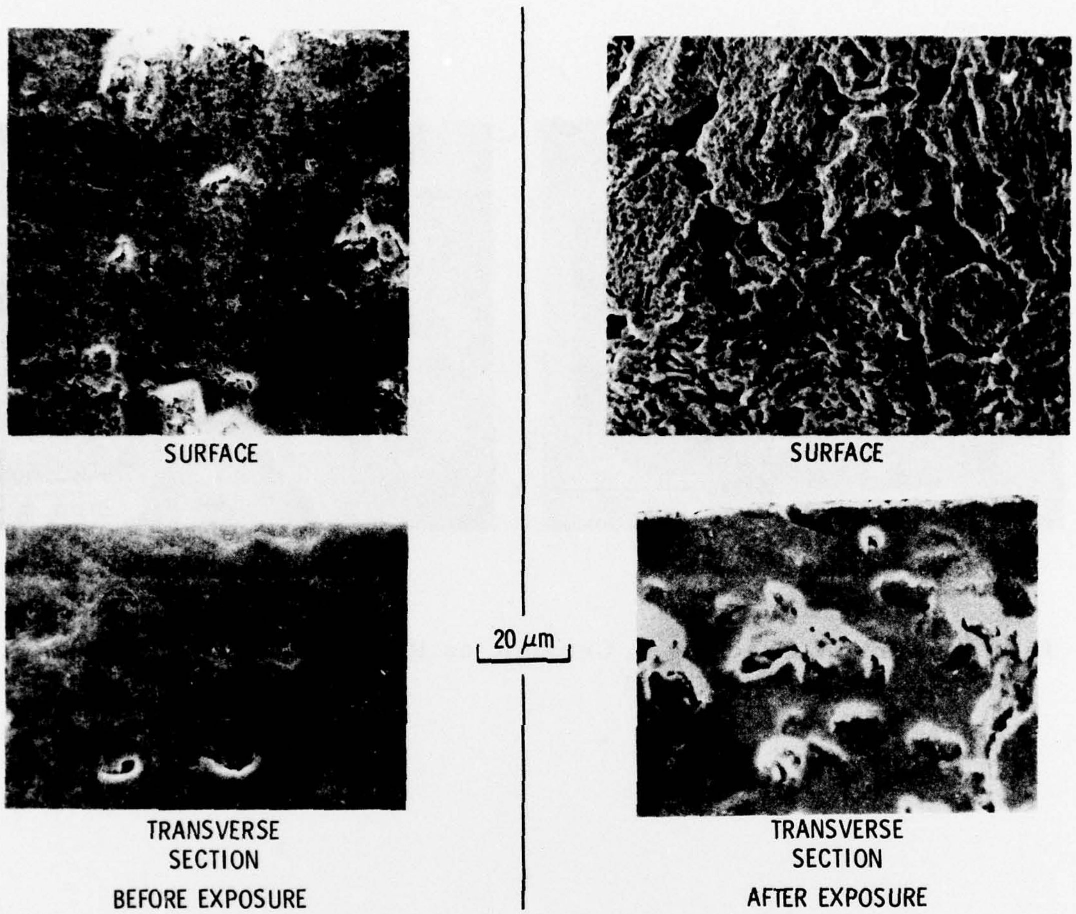


Fig. 7. Sputtering in Graphite Liners with Grain Boundary Cavitation After Single Discharge

V. DISCUSSION

For most of the materials analyzed, surface crack nucleation processes were more serious causes of damage than were the erosion mechanisms. The seriousness of crack initiation, from the standpoint of the lifetime of a structure in a thermal fatigue environment,[23] is shown in Fig. 8. The percentage of life before the formation of a crack is obtained by dividing the number of cycles to failure at a given fatigue stress amplitude by the number of cycles to crack initiation at the same stress amplitude.

A fusion reactor is designed to operate for a large number of cycles before failure, i.e., in the high-cycle fatigue range. In this range, the number of cycles to initiate a crack represents a large percentage of the total lifetime of the structure. Thus, premature failure because of surface crack nucleation may result in a substantially shorter structural duration than predicted from conventional design parameters. Therefore, it is extremely critical that incipient cracking, by the previously mentioned mechanisms, is not initiated early in the predicted lifetime of the various high-load reactor components, since it may substantially lessen the reactor availability because of increased downtime required for more frequent replacements.

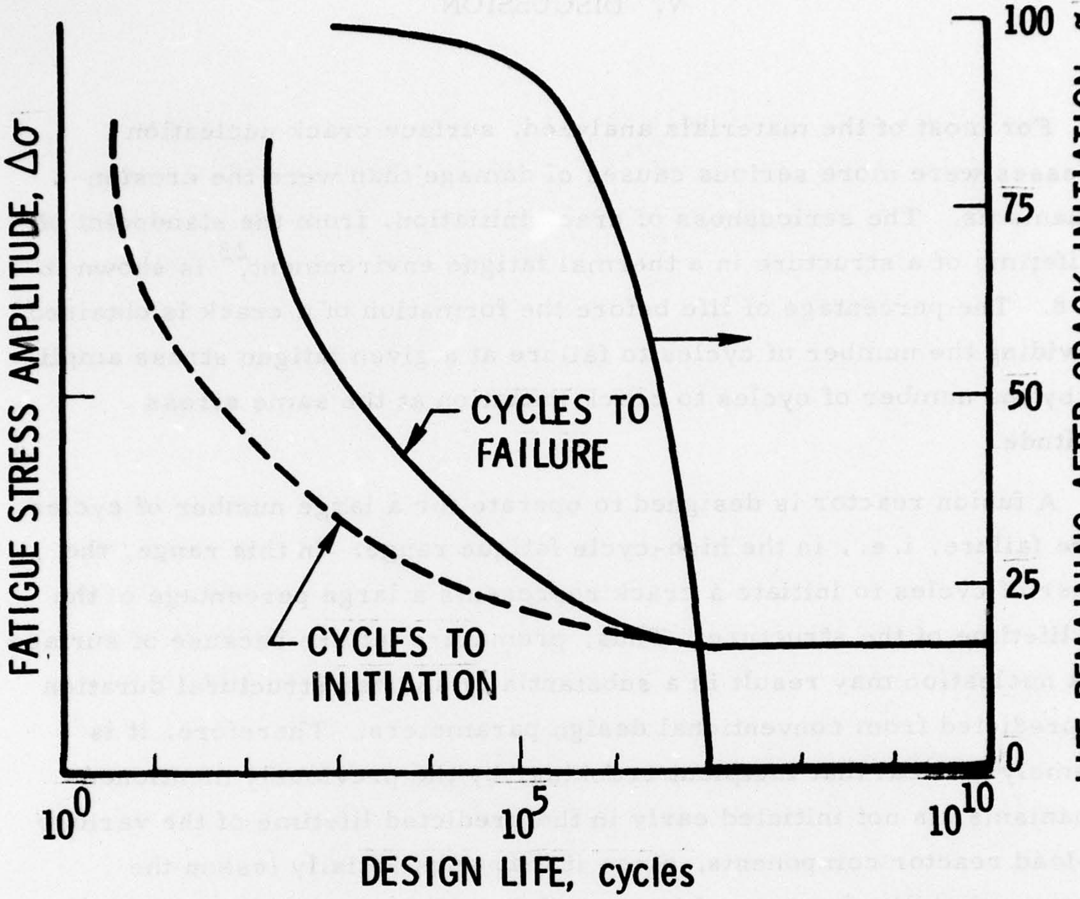


Fig. 8. Effect of Crack Initiation on Structural Lifetime in Thermal-Fatigue Environment

VI. CONCLUSION

In addition to conventional erosion mechanisms, surface crack nucleation damage has been identified in both ductile and brittle potential first-wall materials. These processes can result in a significantly shorter lifetime for high-load reactor components than predicted from high-cycle thermal fatigue analysis and, therefore, should be more precisely characterized.

The DPF can simulate a pulsed fusion reactor plasma because it is capable of generating the temperature conditions and the multisource radiations of particles and photons to which the high-load components and first walls of a fusion reactor will be subjected. The DPF can be used to identify the most critical, or rate-controlling, surface damage processes in specific fusion reactor structural materials. Such proposed first-wall materials[24] as austenitic alloys, iron-chromium-nickel superalloys, and refractory metals and alloys could be tested and evaluated for use in future fusion reactor devices. Additional studies performed on the dense plasma focus under more controlled conditions would be valuable in assessing the full extent of the surface damage to various materials, as well as the damage rates.

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